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Optimization methods applied for Wind–PSP operation and scheduling under deregulated market: A review

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ABSTRACT

This study has been attempted to present the state of art review on the research work carried out for the operation of wind and pumped storage plant (Wind–PSP) under deregulated market. Due to the uncertain characteristics of the wind, power generated by wind turbines is mostly variable and may affect the power system operation. Therefore integrated operation of Wind–PSP requires the knowledge of various factors such as: technology/concept to be used, number and capacity of the generating units, control, management, scheduling and cost of imbalance etc. In order to overcome the effect of variability and above said factors, a joint operation of a wind turbine and energy storage systems (ESS)/technologies is required. Among all the ESSs, PSP is the most mature and large capacity system, which can compensate the wind power uncertainties optimally. Variable operations of PSP, balance the load and generation uncertainty, and thus enhance the ability of power system to incorporate wind power.

The present study has been aimed to cover the review of basics of wind energy, PSP, Wind–PSP system and their current status, applications and challenges involved with Wind–PSP, Operation of Wind–PSP under deregulated market and optimization techniques used in the scheduling of Wind–PSP system. An attempt has also been made to compare the techniques suitable for scheduling of Wind–PSP systems based on earlier research.

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1. Introduction

Today world is facing major environmental challenges like global warming, erratic weather patterns, rising fossil fuel prices, oil insecurity and concerns about climate change casting a shadow over the use of coal, oil and nuclear energy [1,2]. These issues encourage the search for environmental friendly alternative solutions [3,4]. The renewable energy is an inexhaustible and globally available source of energy. Various governments are setting up the targets for renewable energy generation capacity additions. To meet about 15% target of renewable energy contribution in overall energy needs by 2020 [5], major policy measures are required to promote a steep change in the level of renewable energy deployment. As a result, a new energy economy is emerging. This new economy encourages the increase in the contribution of renewable energy sources (like wind, solar, hydro etc.) into the small, medium and large capacity systems.

1.1. Wind power

Wind is the renewable energy source (RES) driven by the sun. The wind is set in motion by the differences in temperature and air pressure due to solar radiation on the earth surface [5–11,13–16]. Wind energy can also help improving industrial competitiveness and have a positive impact on regional development and employment [5,6,8,9]. Presently, wind power plants (WPP) generate electric power at competitive costs and contribute a large share of the power in many countries [7]. As per studies in the European Union, the renewables expected to provide 13.5% of world primary energy by 2030 [10]. The vast majority of these regions have high or medium wind potential which has been exploited greatly in Europe, US and China. On the other hand, the intermittent nature of the wind and the remarkable fluctuations of daily and seasonal electrical load demand in these regions lead to restrict penetration limits of wind energy [7,8] mainly due to technical barriers, which protect the autonomous electrical grids from possible instability problems.

According to global wind energy council (GWEC) and world wind energy association (WWEA), the growth rate of wind energy will increase rapidly and by the year, global wind capacity will rise to 322.4 GW from the 283 GW available at the end of 2012 as shown in Fig. 1 [11–13]. While, the capacity predicted to be installed in 2017 is 536.24 GW, the projected annual growth rates during this period will be average 13.65%. Still the five leading countries, China, USA, Germany, Spain and India, represent together a total share of 74% of the global wind capacity [7–11, 12–20].

With the development from small wind turbines to large capacity WPP, wind power has become more competitive and cheaper [13]. Among other applications of RESs, wind power generation has an edge due to its technological maturity, good infrastructure, relatively competitive cost and environmental benign nature [14]. Germany, Denmark, Spain, Great Britain, India, China and United States, are installing wind power plants on a large scale, in an ever increasing tempo. There are also latest ambitious plans to develop WPPs off shore. Several off shore wind farms are already in line in Europe [7,15]. As the wind-energy technology improvement is going on, the experts predict that the wind power would capture 5% of the world energy market by the year 2020. Advanced wind technology is expected to be more efficient, more robust and less costly than current technology [16]. However, further research will be required in many areas, for example, in the field of wind turbine technology and network integration of medium/high penetration of wind energy. The maximum penetration of wind power in electricity networks is limited by its intermittent nature of energy input and can lead to problems related to system operation and the planning of power systems. Due to the stochastic nature of wind, the energy storage

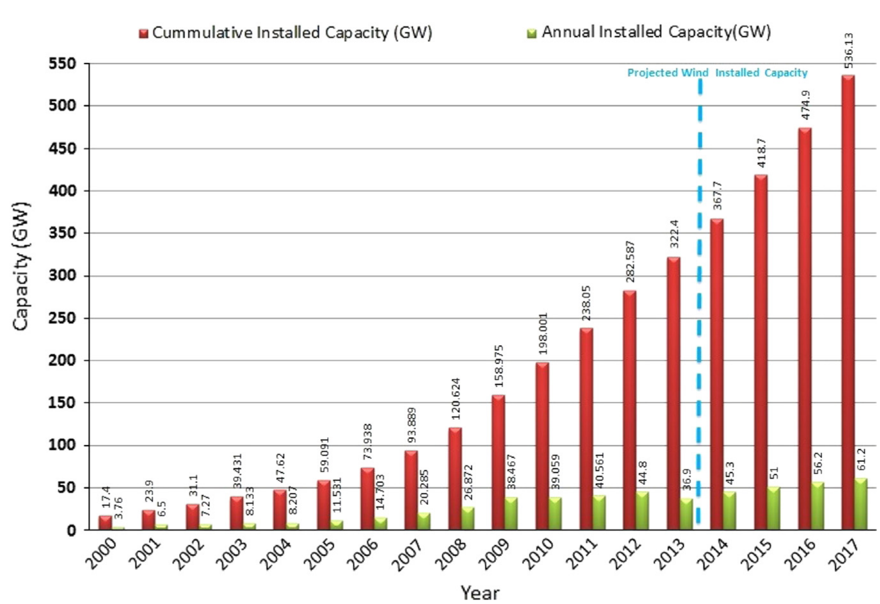

Fig. 1. Global wind energy installed and projected capacity [11–13].

system is undoubtedly very much needed for wind energy technology and to fill up the existing gap between availability and requirement of energy [16].

1.2. Energy Storage Systems (ESSs)

Energy storage systems provide the ability to store power generated by energy systems at times of low demand, and release that energy at times of high demand. In recent years, much effort has been made around the world to develop wind energy resources in response to energy shortage and environmental problems [22]. In regard to this, some of the key applications of ESSs in relation with wind integration are as follows [25–30,32–34]:

- Include load shifting, which uses off-peak storage for on-peak dispatch at the system level.
- Voltage and frequency support at the transmission and distribution level.
- Improvement in power quality, which aids in smoothing fluctuations at the distribution level.

EES is advantageous to the power grid and wind power generators receive higher revenue by providing power to the electricity market when the spot price is high [21]. A wind farm with energy storage system can be classified as a “partially dispatchable” source because of its ability to respond to most situations of high demand [24]. Large scale energy storage is currently not in widespread use as the centralized nature of traditional electricity generation does not require it. Today, storage capacity worldwide is equivalent to about 90 GW i.e. about 2.6% of the total installed capacity of 3400 GW [7,8,11,12,15]. However, many storage options (small, medium and large capacity) have been commercially proven and further being investigated e.g. PSP and compressed air energy storage (CAES) systems; Batteries including Lead-acid (Pb-acid), Sodium–Sulfur (NaS), Nickel–Cadmium (Ni–Cd), Lithium-ion (Li-ion), Flow batteries including vanadium redox battery (VRB) and zinc bromine (ZnBr), Superconducting Magnetic Energy Storage (SMES), Electrochemical Capacitor (EC) and Flywheels [18,20,21,23–25,26–29,31–35]. Energy storage can ameliorate a wind farm's inherent variability. Wind power operators receive higher revenues by providing power to the grid during the peak demand periods when spot electricity price is relatively high [18,27]. A large body of research in the use of energy storage to complement wind power has been undertaken, as reported in the literature [18,20,21,23–25,26–29,31–35,37]. Many technical and power control aspects have been investigated and the research works are available for using energy storage to complement wind power in island locations with isolated grids [28–30].

Due to difference in properties such as response time, storage efficiency, power as well as storage related costs, storage technologies differ with regard to the time scales (intra-hour, intra-day/day-ahead to several days and seasonal level) at which they are suited to support wind power integration. A number of publications reported the benefits and applications of energy storage technologies as mentioned above. Reports published by Electric Power Research Institute and Sandia Laboratory (EPRI [34–41]) discussed potential energy storage applications at generation, transmission, and distribution levels, explored benefits of technologies, and provided cost estimates for technologies in each of the applications such as load shifting, frequency support and power quality. Electrical energy can be converted to different forms for storage as follows [18,19,42–50]:

- as gravitational potential energy with water reservoirs,
- as compressed air,
- as electrochemical energy in batteries and flow batteries,
- as chemical energy in fuel cells,
- as kinetic energy in flywheels,
- as magnetic field in inductors,
- as electric field in capacitors.

Fig. 2 presents a classification of energy technologies based on short, medium and long time scale [25–44,46–50]. Similarly, the comparison of ESS technologies based on various electrical factors like power capacity, energy capacity, efficiency, lifetime etc. [25,27,28,30,32,33,35–45] is given in Table 1.

To have smooth wind power output, studies have focused on the coordination of ESSs with WPPs. The pumped storage plant is the most mature and the largest capacity ESS at acceptable cost among all type of ESSs [20].

1.3. Pump storage system

Electricity storage has the potential benefit of promoting wind technology penetration into the market, as installation of electric storage systems will improve the capacity value of wind generation. All the storage technologies discussed in above section are viable and proven energy storage methods; however, each technology is limited in some way to specifically with wind energy. A CAES system, utilizing underground rock formations, is readily implementable in over 80% of such installation in United States; however, with only 66% efficiency and the use of natural gas firings during operations, the amount of energy lost and the taint of fossil fuels finds a CAES system lacking. A Flywheel system is clean, renewable, and efficient but it is only capable of storing energy over an interval of minutes, if not seconds. The seasonality of wind requires that a storage system store not only over hours in the day but over months in the year. There is significant value in being able to store over shorter time intervals, such as minutes and hours and a system that is capable of storing over a short and long horizon is a valuable asset. Batteries are capable of long term storage and are relatively inexpensive; however, an entire trailer of batteries is necessary to store only 1 MW of power. Wind energy needs an energy storage system having the ability to store thousands of megawatts over a daily and seasonal horizon, the ability to ramp up and down quickly according to real time change in wind energy output at reasonable conversion efficiency. Today, the only storage technology that is consistent with these requirements with the additional benefit of being a mature and developed system is pumped storage system [20].

Using wind forecasts, storage based hydropower plants can adjust their storage and discharges so that they provide energy to the system almost instantaneously, operating much like a peak load plant [44,46–48]. A traditional storage based hydropower plant can be enhanced by pumped hydro storage system (PHSP) or pumped storage system PSP [49].

PSP is a large scale energy storage system. Its operating principle is based on managing the gravitational potential energy of water, by pumping it from a lower reservoir to an upper reservoir during periods of low power demand. When the power demand is high, water flows from the upper reservoir to the lower reservoir, to generate electricity using the turbines. The energy stored is proportional to the water volume in the upper reservoir and the elevation difference of the water in both reservoirs [42] as shown in Fig. 5 [52,54,60,61,135].

PSP has been set up at commercial level for a long time in many countries where the topography is suitable and about over 300 such systems are operating worldwide [42]. In general, the life time of PSP installations is around 30–50 years, with an acceptable both ways efficiency of 70% to 80%, [52,55–59] with some even

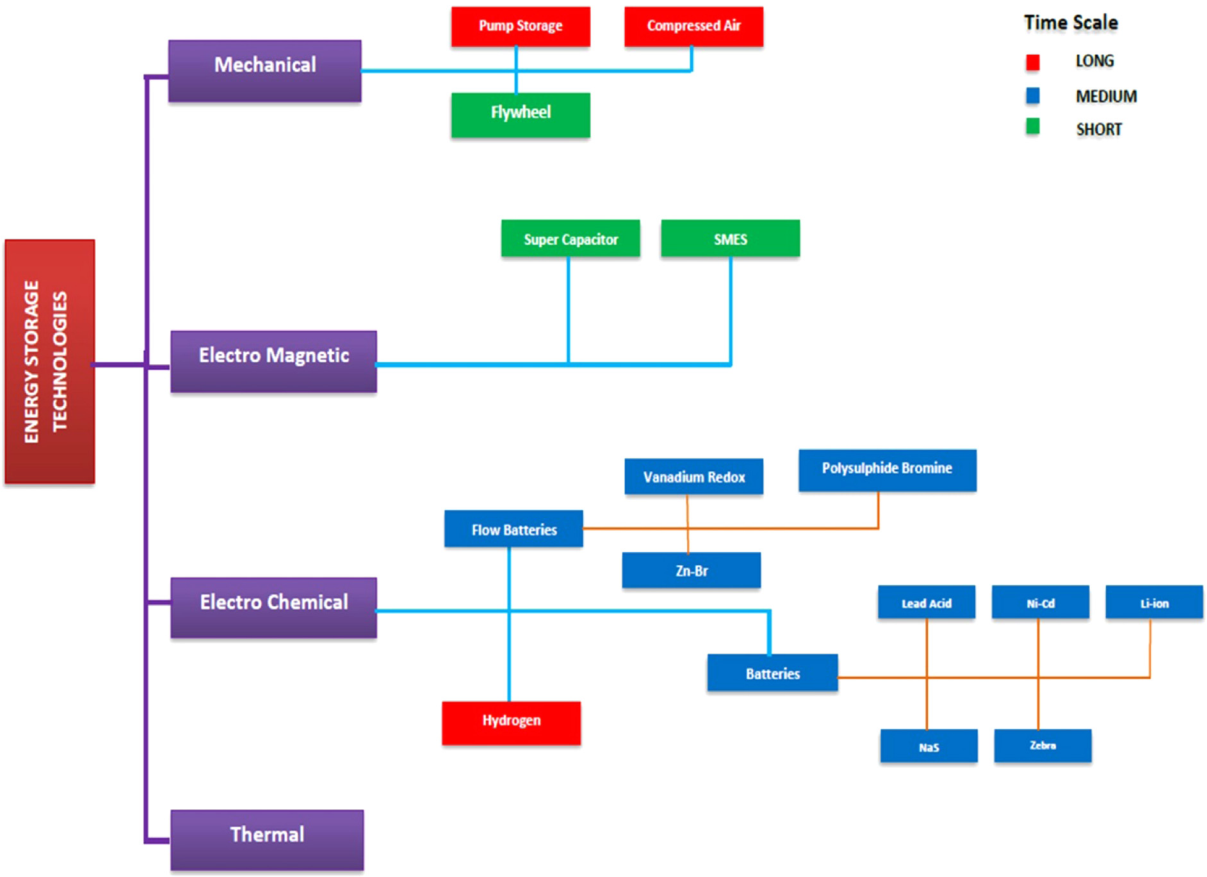

Fig. 2. Energy storage technologies classification [25–44,46–50].

claiming up to 87% [56] and capital costs of 500–1500 US $/kW and generation cost as 10–20 US $/kWh [51-53].

Pumped storage is the largest capacity form of grid energy storage available, and as of March 2012, the EPRI reports that PSP accounts for more than 99% of bulk storage capacity worldwide, representing around 127,000 MW [55]. Globally, there are approximately 270 pumped storage plants either operating or under construction. Of these total installations, 36 units consist of adjustable-speed machines, 17 of which are currently in operation (totaling 3569 MW) and 19 of which are under construction (totaling 4558 MW). The total worldwide PSP capacity is expected to exceed 203,000 MW by 2014, representing an annual growth rate of 10% [63]. The current geographic distribution of the worldwide pumped storage plants is depicted in Fig. 3 [63]. Some of the PSP stations above 1000 MW capacity under construction globally are given in Table 2 [60,61].

The capital costs, suitable geography and the impact on environment are critical factors for the feasibility of PSP [17]. New techniques of utilizing underground caverns or subsurface reservoirs [36,37] are opening up the possibilities of using PSP in areas other than mountains.

Recent examples of PSP include, the proposed Summit project in Norton (USA) and the Mount Hope project in New Jersey (USA), to use old iron mine as the lower reservoir [38]. Several other new underground pumped storage projects have been also proposed. Though cost estimates for these projects are higher than the surface power projects, but their use might greatly expand the number of pumped storage sites. A 30 MW, Yanbaru PSP project in Okinawa was the first demonstration project of seawater pumped storage [55]. A 300 MW seawater based project has recently been proposed on Lanai, Hawaii [60] and several seawater-based projects have recently been proposed in Ireland [61]. Developing additional hydropower pumped storage, particularly in the areas with increased wind and solar installations, would significantly improve grid reliability while reducing the need for construction of additional fossil fueled generation.

1.4. Wind–PSP system

Among the different possibilities of controllable power producers to operate in coordination with wind power, PSPs are the most feasible solution due to their high flexibility as they can change their output power approximately 100% within minute [68]. Their ability to quickly change the output power is the key feature to follow the short term variations on wind power [26,37]. The main objective of such integration is to limit the active power output variations of wind energy resource taking into account the grid needs and the available stored energy [60–62,64–69]. In this context, the integration of wind with pumped storage for shaping wind variability may be observed in Fig. 4 [61]. Large scale integration of wind power in power system requires large ESS technologies such as PSP. In the recent years, the combined use of Wind–PSPs has started receiving attention from the scientific community. A typical arrangement of Wind–PSP system is shown in Fig. 5.

The possibility of connecting a pumped storage unit with electric grids is of great importance in order to reduce the cost of combine Wind–PSPs, since such a unit has a considerable value in its own right and can operate not only with wind power but also with any other power generation systems like hydro, solar, thermal etc [67].

Due to advancement in wind energy technology recently, higher penetration rate of wind power in electrical system is expected and the wind power should not be considered as marginal sources. Due to increase in wind energy generation

Table 1
Comparison of various ESS technologies [25,27,28,30,32,33,35–45].

Technology type	Storage capacity (MWh)	Power capacity (MW)	Energy density (KWh/m^3)	Cycle life (years)	Access time	Self-discharging	Efficiency (%)	Power/Energy	Environment impact	Application	Installation examples	Suitability with wind (Yes/No)
Flywheel	2.5	25 MW	1000	20 Year	ms	1–10%	90–95	25 MW for 5 min or 5 MW for 30 min	Small	Power quality improvement and Transportation defense	– Usually utilized for UPS – Propulsion applications like engines and road vehicles	Yes
Capacitors	Small	Large	5	10^6 Cycles	ms	10% day	90–95	Rated power for sec. up to several min	Medium	Power quality, emergency bridging power, Consumer electronics	–	Yes
SMES	0.5–5	10	2.8	20 Year	ms	Cooling power	90–95	High power for several sec	Small	Power quality and T&D applications	– Several used in power quality control – In Wisconsin a string of distributed SMES units was deployed to enhance stability of a transmission loop	Yes
NaS Battery	Up to 1200	Up to 200	400	4500 cycles up to 15 year	ms	No	80–90	Rated power for hours, very high power for minutes	Medium	Variability reduction, Uninterruptable power supply (UPS), T&D applications, Power quality improvement	– Rokkansho, Japan 34 MW/ 245 MWh – Hittachi Plant 8 MW/58 MWh	Yes
Pumped Storage	500–8000	30–4000	–	Up to 50 year	1–3 min	No	70–85	Rated power for long time	High	Spinning/standing reserve, energy arbitrage	There is over 90 GW in more than 240 Pumped storage facilities in the world	Yes
CAES	500–2500	50–300	–	Up to 40 Year	10 min	–	64–75	Rated power for long time	Medium	Spinning/Standing reserve, energy arbitrage, Frequency regulation	– Huntorf plant, Germany, 290 MW580 MWh – Mclntosh plant, USA, 100 MW, 2600 MWh	Yes
Hydrogen	1000	100	–		–	–	30–50	Rated power for long time	Medium	Variability reduction, Spinning/ Standing reserve	–	Yes

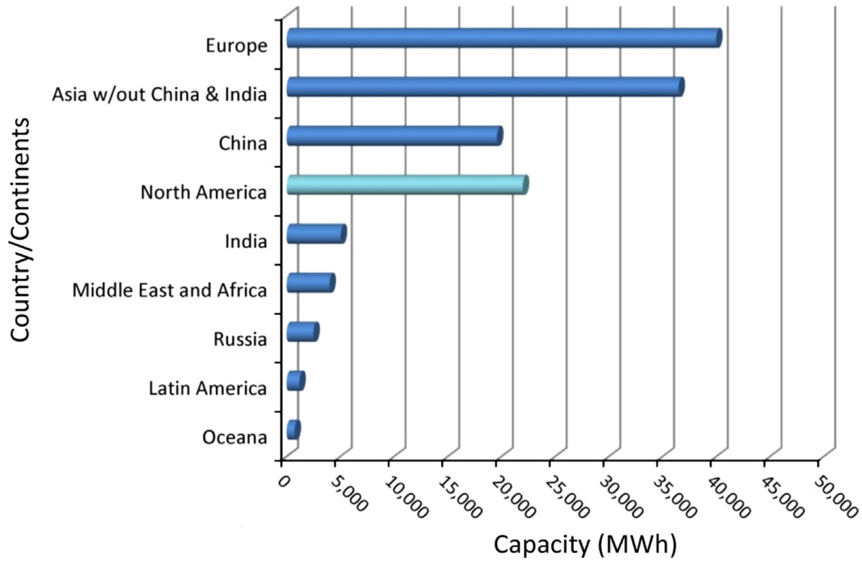

Fig. 3. Geographic distribution of pumped storage plants (as on April 2013) [63].

Table 2
PSPs above 1000 MW capacity under construction (as on April 2013) [60].

Station	Country	Capacity (MW)	Expected completion
Kannagawa hydropower plant	Japan	2820	2020
Dniester pumped storage power station	Ukraine	2268	2017
Jixi pumped storage power station	China	1800	2018
Kazunogawa dam	Japan	1600	2014
Liyang pumped storage power station	China	1500	2016
Ingula pumped storage scheme	South Africa	1332	2014
Qingyuan pumped storage power station	China	1280	2015
Hohhot pumped storage power station	China	1224	2013
Hongping pumped storage power station	China	1200	2015
Xianyou pumped storage power station	China	1200	2013
Siah Bishe pumped storage power plant	Iran	1040	2013
Upper Cisokan pumped storage power plant	Indonesia	1040	2016
Linth-Limmern pumped storage station	Switzerland	1000	2015
Tehri pumped storage power station	India	1000	2016

in the total electricity, there may be large fluctuation which system networks cannot tolerate. Thus more constraints will be introduced to wind power producers e.g. limit of injected power variation, higher service quality (current and voltage profile, ancillary service) etc. [68].

Recent Wind–PSP application trends in Europe may be seen which provide increase in wind energy upto 8% of energy (53 GWh) and in selected regions $>20\%$ penetration with adjustable/variable speed focus on new and re-optimization of existing plants. European approach towards pumped storage is spreading globally now. In Denmark, there is 30% wind penetration in the generation mix with no native load balancing. Excess wind energy is exported and stored in Norwegian hydropower reservoirs [71].

The Alta Mesa pumped storage facility near Palm Springs, CA uses wind generated electricity to accomplish the pumping to the upper reservoir. The Pumped Storage project is a 70 MW energy storage facility. This facility is able to store 420 MWh and produce output for 6 h continuously. Additionally, this project produces 130,000 MWh per year of high-value on-peak power, and uses 175,000 MWh per year of low-value off-peak power [71,72].

During the recent years, a number of studies have been performed on the development of Wind–PSP systems mainly in USA and Europe [60–72]. Wind–PSP technology has advanced significantly since its introduction and now includes improved efficiencies with modern reversible pump-turbines, adjustable-speed pumped turbines, new equipment controls such as static/variable frequency converters and generator insulation systems, as well as improved underground tunneling construction methods and design capabilities. Overall, the pumping/generating cycle efficiency has increased pump-turbine generator efficiency by as much as 5% in the last 25 years, resulting in energy conversion or cycle efficiencies greater than 80% [73].

Wind Power generation even being highly variable, penetrated in power market very well due to conducive policy environment. PSP can compensate wind power uncertainties e.g. fluctuation suppression, oscillation damping, spinning reserve, peak shaving, transmission curtailment, time shifting, unit commitment, seasonal storage etc. optimally. Therefore, a review is presented on the research work carried out for optimal planning of Wind–PSP systems under the deregulated market with the potential challenges, their solution and the optimization tools.

2. WIND–PSP concept

In order to provide the efficient operation of Wind–PSP system and maximization of the profit, some operation management tools are required. Both of these systems have their own merits and demerits. In coordination of both the systems, one can compensate these demerits and work as complimentary for each other to provide the efficient operation [34,54,61–66,69,71,73,74–76].

2.1. Operation of wind power plant

Wind turbine is used to convert the kinetic energy of the moving wind into mechanical energy with the help of a rotor consisting of hub and blades [76]. The kinetic energy of the wind

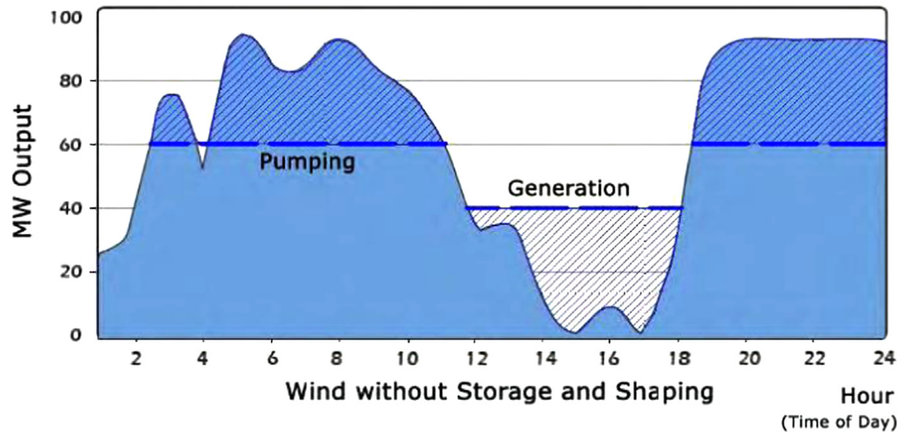

Fig. 4. Integrating wind with pumped storage for shaping wind variability [61].

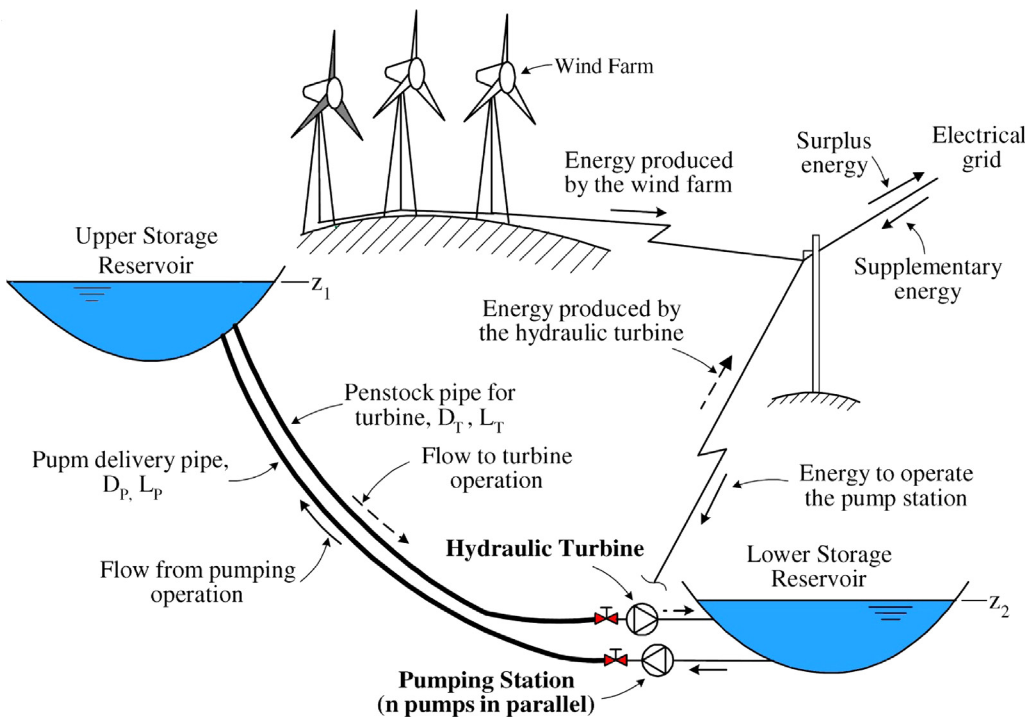

Fig. 5. Typical arrangement of Wind–PSP system [52,54,60,61,135].

(E_k) is given by Eq. (1), where, m is the mass of moving air and V is the air velocity.

$$E_k = \frac{1}{2} m V^2 \tag{1}$$

The mass of wind changes with change in the wind velocity and can be defined by Eq. (2)

$$m = \rho V A t \tag{2}$$

where, ρ is the wind density, V is the velocity of air, A is the swept area of blades and t is the time deviation. Therefore, the total energy (E_k) and the power (P_k) across the input of wind turbine rotor are given in Eqs. (3) and (4) respectively.

$$E_k = \frac{1}{2} \rho A V^3 t \ \text{(Joules)} \tag{3}$$

$$P_k = \frac{1}{2} \rho A V^3 \ \text{(Watts)} \tag{4}$$

The rotor connected across the wind turbine convert the power of moving air into the mechanical power, which result in a reduced speed in the air mass. The theoretical optimum power across the output of the wind turbine is given by Eq. (5).

$$P_m = \frac{1}{2} \rho A V^3 C_p \ \text{(Watts)} \tag{5}$$

where, C_p is the Betz constant. The wind turbine rotor mechanically coupled with electrical generator [77], converts this mechanical energy (P_m) into electrical energy (P_e) and supply to the power grid as given in Eq. (6), where η_m is the mechanical efficiency and η_e is the efficiency of electrical generator.

$$Pe = \frac{1}{2} \rho A V^3 C_p \eta_m \eta_e \tag{6}$$

2.2. Operation of pumped storage plant

The basic concept of operation of pumped storage plant is very much similar to the conventional hydro power plant. The power generated by PSP in the generating mode P_{gen}, depends on the rate of flow of water $q_{t'}$, from upper reservoir to lower reservoir. h and n_{th} are the head (difference in level between upper and lower

reservoir) and the efficiency of PSP in generating mode, as given in Eq. (7).

$$P_{gen} = g q_{t'} h \eta_{th} \tag{7}$$

In the pumping mode, P_{pump} is the amount of power consumed by the PSP for pumping the water from lower reservoir to upper reservoir, as given by Eq. (8), where n_p is the pumping efficiency and t" is the operating time of PSP in pumping mode.

$$P_{pump} = \frac{g q_{t''} h}{\eta_p} \tag{8}$$

$$t = t^{'} + t^{''} \tag{9}$$

where, t' is the operating time of PSP in generation mode, t is the total time, g is the gravitational constant and $q_{t''}$ is the amount of water pumped by PSP.

The water storage of upper reservoir for the PSP is given by the Eq. (10), where V_t and V_{t+1} are the volume of water stored in upper reservoir during tth and $(t+1)$th time respectively. Water inflow and reservoir spillage have been neglected in this equation.

$$V_{t+1} = V_t + q_{t''} - q_{t'} \tag{10}$$

The energy equation for PSP has been derived below as Eq. (11) by substituting qt' and qt'' from the Eqs. (7) and (8) in the Eq. (10).

$$(V_{t+1} - V_t)hg = \left(P_{pump} n_p - \frac{P_{gen}}{n_{th}} \right) \tag{11}$$

By multiply time deviation on both sides of Eq. (11), we get

$$(P_{t+1} - P_t)\Delta t = \left(P_{pump} n_p - \frac{P_{gen}}{n_{th}} \right) \Delta t \tag{12}$$

$$E_{t+1} = E_t + \left(P_{pump} n_p - \frac{P_{gen}}{n_{th}} \right) \Delta t \tag{13}$$

where, P and E are the power and the energy stored in the PSP reservoir respectively.

2.3. Combined operation of Wind–PSP

Under the deregulated market, power producer participate by placing the energy bid in the market. Power producer has to pay the penalty for the market imbalances, which occur due to the difference between the contracted bid and produced energy. To reduce the impact of wind uncertainties, power producers need ESSs, to maintain the reliability and balance across the power system. Pumped storage technology is always seen to be the best option as an ESS for WPPs [77–80] and provides significant flexibility in switching operation. The different modes of operation of Wind–PSP are as follows [4–23,35–39,46,54,67,78,81,82]:

1. **PSP generating mode:** In this mode, PSPs supply power to the grid connected day ahead market and try to increase their revenue. In this mode, both wind and PSP pumps would remain at their idle condition.
2. **PSP pumping mode:** In this mode, PSPs operate in pumping mode to consume the wind generated power and store it in upper reservoir in the form of water.
3. **Grid pumping mode:** In this mode, PSP utilizes the grid power via pumping action and store it in the upper reservoir in the form of water. Mostly this operation is done whenever; the market price of electricity is low.
4. **Wind generating mode:** In this case, WPP supply the power directly to the grid and PSP remains at its ideal condition.
5. **Wind–PSP mode:** In this mode, both wind and PSP system provide the combined operation to increase the overall revenue. In this mode, PSP operates either in generating mode or in pumping mode, in order to compensate the variation of wind power.

3. Challenges and opportunities for Wind–PSP development under deregulated market

Even though there are lots of benefits of Wind–PSP system in coordination mode, it has many challenges. The challenges concerning to the operational aspects of Wind–PSP as well as its penetration in the market cannot be ignored. An essential attribute of electric power system is grid reliability-ensuring that electric generation matches the demand in real-time. The primary challenge in ensuring reliability is that electricity has no shelf life; it must be generated when needed. Electricity demand continuously changes, especially between day-time periods of peak demand and night-time periods of low demand. Developing additional Wind–PSP, particularly in areas with recently increased wind and PSP capacity, would significantly improve grid reliability, while reducing the need for additional fossil-fueled generation. While benefits of expanding Wind–PSP capacity are clear, current market structures and regulatory frameworks do not present an effective means of achieving this goal. Thus, policy changes are needed to support the development of additional grid-scale energy storage [83–85].

3.1. Major challenges to Wind–PSP systems

3.1.1. Wind power challenges

In order to attain optimal management of the system, it is necessary to include the information on uncertainty of wind power predictions, as well as the use of optimization tools. Wind speed prediction was until recently considered for weather analysis only. Now, the high level of penetration of wind generation in electric systems has resulted in the increased importance to the prediction of wind speed. Injection of wind power into the grid has zero operational cost and hence to be used fully. An imbalance in the expected wind power generation may significantly modify the market operation, requiring additional power reserves in the system operation. For this reason, new tools are necessary to provide reliable information about wind power generation and to compensate the probable imbalances in wind power generation.

The penetration limits of wind energy may lead to severe financial loss to the wind farm owners and discouraging future investments in wind energy applications [4,10]. To solve these problems and to establish wind power as dispatchable electricity generation solution, the recovery of the excess wind energy is prerequisite. For this reason, ESSs which are able to recover the not injected wind energy [11–15] under economically effective terms [16,17] are widely applied, achieving maximum exploitation of wind energy at both national [18] and community level [19] applications. The wind power growth faces following issues [7,15,34–38]:

- grid availability and capacity,
- low, medium and high growth rate,
- required new economic incentives,
- encouraging and favorable wind power policies,
- reliable wind resource assessments,
- proper siting and sizing of WPPs,
- operational issues (short and long term balancing, stability in grid network, frequency control, transmission and distribution impacts with WPPs, unit commitment, economic dispatch etc.),
- operational and maintenance issues,
- network integration issues (reactive power control, voltage control, short circuit power control, flicker control, harmonics control etc.),
- environmental issues (physical impacts, flora and fauna, sound propagation, shadows and reflexes etc.).

3.1.2. Pumped storage challenges

3.1.2.1. Environmental issues for storage siting. Significant environmental misconceptions are faced by many pumped storage developers. In the past, almost all the pumped storage projects were required the construction of at least one dam along the main river, altering the ecology of the river system [83,84]. Enhanced awareness of the impacts from construction of large dams and storage reservoirs on river systems generally preclude further consideration of these large projects, or developers work directly with the environmental community in order to reduce or mitigate project impacts [85].

The majority of existing pumped storage project owners (typically investor/publically owned utilities) has attempted to address these impacts through significant post-construction efforts to provide project-specific mitigation measures.

In today's pumped storage development community, project proponents attempt to minimize these issues by focusing on new project sites, where proposed construction would have minimal environmental impacts, rather than attempting post-construction mitigation measures [83,86].

A relatively new approach for developing pumped storage projects is to locate the reservoirs in areas which are physically separated from river systems. These projects are termed as "closed-loop" pumped storage and they have minimal or no impact on river systems. After initial filling of the reservoirs, the additional water requirement is minimal operational make-up water required to offset evaporation or seepage losses. By avoiding existing complex aquatic systems entirely, these types of projects have the potential to greatly reduce the most significant aquatic impacts associated with project development. In addition, because closed-loop pumped storage systems do not need to be located near an existing river system or body of water, with the right topographical features, they can be located where needed to support the grid [34–36,87].

3.1.2.2. Regulatory treatment of pumped storage plants. Another significant challenge forced by the pumped storage project developers is the regulatory timeline for development of new projects. Under the current licensing process worldwide, obtaining a new project license may take three to five years or even more before the developer may begin project construction. There is currently no alternative licensing approach for low-impact or closed-loop sites to shorten this time frame [88]. This requires a policy change.

In addition, a three to five year construction period is common for most large projects; furthermore, environmentally benign projects being developed to support renewable energy integration could take six to 10 years or longer to construct. Except this, the lack of availability of financial institutions for financing such type of long lead projects through the licensing timeframe is another challenge [34,36,37,38,89,90].

3.1.2.3. Existing market rules and impact on energy storage value. In existing market rules and due to impact on energy storage value in today's electricity market, pumped storage has the potential to bring added value through ancillary services. However, a lack of energy policy may lead to change independent system operators (ISO) market rules and product definitions that may have significant impact on the value of ancillary services, including those related to energy storage. For example, in the United States, Federal Energy Regulatory Commission (FERC) Orders 890 and 719 required ISOs to modify their tariffs and market rules so that all non-generating resources, such as demand response and energy storage can fully participate in established markets [36,83,85,89].

These are real-time or day-ahead markets and there are no long-term value streams, where a bulk storage project can attract investors seeking revenue certainty through long-term power purchase agreements or defined value streams [37,91].

3.1.2.4. Struggle over generation or transmission. Energy storage technologies have the ability to provide components of transmission assets along with their ability to supply ancillary services and alleviate congestion by absorbing excess generation. Market rules generally prohibit transmission assets from participating in wholesale energy and ancillary service markets to maintain the independence of grid operators and avoid the potential for market manipulation, whether real or perceived [84,92–94].

In addition, the policy prohibits sales of ancillary services by a third-party supplier to a public utility that is purchasing ancillary services to satisfy its own obligations to the customers under its open access transmission tariff. This restriction removes one of the largest potential markets for bulk-scale storage. This clear distinction between transmission and generation assets is problematic for energy storage [37], because pumped storage or other energy storage projects have components of both transmission and generation.

3.2. Major solutions and recommendations to the development of Wind–PSP systems

Contrary to above challenges, the factors supporting the case for Wind–PSPs can be summarized as follows [34–37,83–93,94]:

- The strong push for "carbon free generation" leads advances in solar, wind and other renewables, which causes the need for energy storage products.
- Energy storage technology cost comparison.
- New technology developments in Wind–PSP affecting current and Wind–PSP projects.
- Market drivers behind international Wind–PSP development.
- Some areas of world (Europe) have stronger, well-defined ancillary service markets.
- High volatility between on-peak/off-peak electricity prices drives energy arbitrage opportunities.
- PSP is often considered the proven grid-scale energy storage technology.
- There are various incentives for energy storage, including capacity payments and reduce transmission interconnection fees.
- Regulated utilities build and operate Wind–PSPs as a key load management element of their operations.
- Recognize the energy security role in the domestic electric grid.
- Facilitate an energy market structure, where transmission providers benefit from long-term agreements with energy storage facility developers.

3.3. Wind–PSP and deregulated market

In a vertical integrated power market, electricity is provided to consumers by public or private utility monopolies. The main aim of this structure is to meet consumer demand and ensure the reliability of power system [95]. The main problem in vertical integrated market is the lack of competition and relatively low improvement in technology. In the electricity market, there is large variation in consumer demand day by day. It is required to improve each sector of power system as well as to increase the transmission capacity rapidly with time, which is not possible in vertical integrated type market structure. Due to these problems, various electrical utilities switch towards the deregulated market

structure. After 19th century, several countries like U.S., U.K., Spain and Norway started to deregulate and privatized their power market structures, which are characterized by open competitive energy markets, unbundling electricity services and open access to the network [96]. In this structure, vertical integrated market divided into different independent entities and the deregulated market also integrated with other power market, so that different entities should compete with each other in order to maximize their profits [97]. To establish the competitive market, the generating entities try to provide the improvement in their technology as well as the generation capacity. This leads to efficient power system with better quality of service.

3.3.1. *Types of deregulated market*

The regulated sector is comprised of private or public owned local monopolies, but has prices, revenues and/or profits regulated by government appointed electricity regulator. Deregulation is the process by which parts of the regulated sector are opened for competition. The generation sector has generally been open to competition for a long time, even when the dominant incumbent generator is regulated. Generation competition is not usually classed as deregulation. Almost always, deregulation begins by a gradual opening of the supply sector to competition, starting with the very large consumers, with a phased opening of the market to small consumers and eventually residential consumers [98].

There are a range of possible market rules for pumped storage. The plant may be able to draw desired power at a known fixed price (as in most demand in the pool), or required to contract the power purchase in advance (as in the bilateral market) [95].

The most advanced market is the Pennsylvania–New-Jersey–Maryland (PJM) market in USA, with location marginal pricing, a form of capacity markets and monetization of ancillary requirements and provision [99]. This has three key elements – a spot or day ahead market, ancillary services market and Real Time Market [95,98,100]. Region wise annual and cumulative wind energy penetration in different markets is shown in Table 3 (as on April 2013) [13].

3.3.1.1. Spot or day ahead market. The spot or day-ahead market is a forward market in which clearing prices are calculated for each hour of the next operating day based on generation offers, demand bids, bilateral transaction schedules, incremental and decremental bids which are purely financial bids to supply and demand energy in the day-ahead market. Day-ahead market enables market participants to purchase and sell energy at binding day ahead nodal prices. All spot purchases and sales in the day-ahead market are settled at the day-ahead prices [95,98].

3.3.1.2. Ancillary services market. Ancillary services are needed for the power system to operate reliably. In the regulated industry, ancillary services are bundled with energy. In the restructured industry, ancillary services are mandated to be unbundled from energy [100,101]. For example, four types of ancillary services including regulation, spinning reserve, non-spinning reserve, and replacement reserve are traded, which are from the highest quality to the lowest quality [102–104]. The market would be cleared first for regulation, then spinning, non-spinning, and replacement reserves. In addition to this, the basic list of ancillary services is as follows [95,98,100–104]:

i. frequency control/voltage regulation,
ii. operating reserves (Spinning reserve and Non-spinning reserve),
iii. real-power-loss replacement,
iv. scheduling and dispatch,
v. load following,
vi. energy imbalance.

3.3.1.3. Real time market. The real-time balancing market is based on actual real-time operations. Generators those have selling capacity represent capacity resources must offer their energy in the day-ahead market [98]. Any resource that is a capacity resource must offer its energy in the day-ahead market, regardless of any associated bilateral energy contracts. Available capacity resources that are not selected in the day-ahead scheduling (e.g., the offer price was higher than other generators and therefore the resource was not economically dispatched) may alter their bids for use in the real-time balancing market. If a generator chooses not to alter its bid, its original bid in the day-ahead market remains in effect [99,101–105].

4. Scheduling of Wind–PSP systems

Scheduling of generating units is done to ensure that consumer side demand is balanced with scheduled bids. It is usually prepared in advance in the deregulated or day ahead market. During this process, the electric system operator seeks to optimize the total generation by minimizing its operating cost to increase overall profit [106]. Large amounts of intermittent wind power generation can cause efficiency losses across the market, because in real time other generating sources would have to be rescheduled and be operated below their economically optimum level to manage the difference between the scheduled wind generation and the actual wind generation. In order to reduce these differences, the quality of the wind forecast technique is a significant factor to control this impact, because high prediction errors of wind power can result in high imbalance costs.

The wind forecasting techniques are not so accurate at present. Thus, modeling the uncertainty of predicted wind power generation

Table 3
Region wise annual and cumulative wind energy penetration in different markets (as on April 2013) [13].

Region	Annual installed wind capacity in GW/(%)		Cumulative installed wind capacity GW/(%)		Market type
	Actual 2012	**Forecast 2013**	**Actual 2012**	**Forecast 2013**	
Europe	12.7 (28.3%)	10 (25.2%)	109.8 (38.9%)	119.8 (37.1%)	Pool based
North America	14.9 (33.3%)	6.5 (16.4%)	67.6 (23.9%)	74.1 (23%)	Open access
Asia	15.5 (34.6%)	19 (48%)	97.6 (34.5%)	116.6 (36.1%)	Open access
Latin America	1.2 (2.7%)	2.8 (7.1%)	3.5 (1.2%)	6.3 (2%)	Open access/Pool based
Pacific	0.4 (0.9%)	0.8 (2%)	3.2 (1.1%)	4 (1.2%)	Open access
Middle East and Africa	0.1 (0.2%)	0.5 (1.2%)	1.1 (0.4%)	1.6 (0.5%)	Open access
Total in GW	**44.8**	**39.6**	**282.6**	**322.4**	
Growth Rate (%)	**10.80**	**−11.60**	**18.70**	**14.10**	

is a serious issue for the wind producers. To improve the wind operation under deregulated market, a pumped storage plant may be added with wind system [107,108].

In last few years, these aspects have been studied by several researchers. An optimization approach is applied to the operation of a wind-hydro pumping storage power plant, considering the requirements of storage capacity by Castronuovo et al. [109]. The authors proposed a similar model in other study [110], including the stochastic characteristics of the wind power. By considering the various issues such as the production variability and uncertainty of wind facilities, the eventual future decline in wind power investment costs, and the significant financial risk involved in wind power investment. Baringo and Conejo [111] discussed a risk-constrained multi-stage stochastic programming model to make optimal investment decisions on wind power facilities along a multi-stage horizon. Kaldellis et al. [112], performed a parametric analysis of a combined wind-hydro plant in a medium size island of the Aegean Archipielago. A pumped hydro storage system is proposed to increase the penetration limits of wind power in Canary Island [113]. The author carried out economic feasibility of a PSP in an isolated system with high thermoelectric production and wind energy rejection [114].

Recently, Hosseini [115] proposed a technique based on stochastic programming to optimally solve the wind power problem faced by the uncertainty for a wind power producer in a short-term electricity market, while limiting the risk of expected profit and required reserve due to wind speed forecast volatility. Inherently intermittent nature and imbalance costs of wind power were paid and cope up by wind farm owners. Moghaddam et al. [116] developed a stochastic profit-based model for day-ahead operational planning of a combined wind farm-cascade hydro system. The proposed optimization problem was a mixed integer linear programming (MILP), formulated as a two-stage stochastic programming model which applied on a real case study. Similarly, a unit commitment model which accounts for the uncertainty in wind power in the Irish power system was presented by Tuohy et al. [117]. A stochastic programming approach was proposed to allow evaluating alternative production and offered strategies to submit to the electricity market with the ultimate goal of maximizing profit along with the innovative comparative study, where the imbalances were treated differently by Pousinho et al. [118].

5. Optimization techniques for Wind–PSP scheduling

Optimization tools (techniques) are required for optimal scheduling so that the electric system operators can optimize the total generation and minimize its operating cost as well as increase overall profit. An efficient generation schedule not only reduces operation costs, but also increases system security and maximizes the energy efficiency of the hydro reservoirs [119,120]. Optimization techniques constitute a suitable tool for solving complex problems in the field of Wind–PSP systems scheduling. In tackling the problems related to Wind–PSP scheduling, many studies have been performed by earlier researchers. Most of these studies have delivered promising results in terms of reducing operating costs and increasing system security. Researchers are continuously proposing and applying new methods. A critical review of different techniques employed in Wind–PSP schemes has been carried out in this study. For ease of reference and to facilitate understanding, these are categorized and discussed into three major headings based on problem formulation, forecasting technique and market type used as follows:

i. Classical optimization techniques for Wind–PSP scheduling.
ii. Artificial intelligent optimization techniques for Wind–PSP scheduling.
iii. Other promising programming techniques for future use for Wind–PSP scheduling.

The benefits as well as drawbacks of each optimization technique are reviewed based on the major scheduling constraint i.e. optimal pumped storage operation schedule, operating costs, maximizing the energy efficiency, profit maximization and imbalances cost.

5.1. Classical optimization techniques for Wind–PSP scheduling

The classical methods of optimization are useful in finding the optimum solution of continuous and differentiable functions. These methods are analytical and make use of the techniques of differential calculus in determining the optimum points. Since some of the practical problems involve objective functions that are not continuous and/or differentiable, the classical optimization techniques have limited scope in such practical applications [121,122].

The classical optimization methods used in Wind–PSP scheduling are based on Interior Point Method (IPM), Linear Programming (LP), Mixed-Linear Programming (MLP), Stochastic Programming, Two Stage Stochastic Programming, Multi-criteria Optimization, Two Stage Min–Max Optimization, Monte-Carlo Simulation, Decomposition Algorithm and MLIP with CPL and CPLEX solver. While number of research papers tackle these problems using heuristic optimization methods, especially Genetic Algorithms, Particle Swarm Optimization (PSO) etc. Additionally, the forecasting techniques under classical optimization used by earlier researchers are Monte Carlo, Fuzzy Clustering Algorithm, Input/Output hidden Markov Model (IOHMM), Probabilistic Distribution, Historic Time Series Extrapolation etc. Most of the reviewed work reported here under classical optimization techniques is based almost on the same objective i.e. to minimize the operating cost or maximize the profit. Although, the literature available on Wind–PSP's scheduling is limited due to the complex combinational structure of the system.

In the classical optimization techniques reviewed in this study, it is seen that Castronuovo et al. [110], Brown et al. [123], Garcia-Gonzalez et al. [124], Ummels et al. [125], Jiang et al. [126], Faias et al. [127] tried to minimize operating cost and maximize Wind–PSPs profit considering the autonomous island power system and in spot or day ahead market.

Castronuovo et al. [110], proposed an hourly-discretized optimization algorithm (i.e. LP and IPM) to identify the optimum daily operational strategy to be followed by the wind turbines and the hydro generation pumping equipment. The stochastic characteristics of the wind power were considered by using a time series, for a time horizon of 48 h, of average values and standard deviations representing the wind-power forecast using Monte Carlo simulations (wind-power time-series scenarios) in an autonomous island to maximize the profit. The authors provided best bidding strategy for Wind–PSP system but not considered the risk analyses. Brown et al. [123] also minimized the operating cost using LP with CLP solver for an autonomous island. Here, Fuzzy clustering algorithm is used for Wind–PSP scheduling and dynamic security criteria is considered without risk assessment. Garcia-Gonzalez et al. [124] investigated the combined optimization of a wind farm and a pumped-storage facility from the point of view of a generation company in market environment for profit maximization. The optimization model was formulated as a two-stage stochastic programming problem based on Mixed Integer Linear Programming (MILP) using CPLEX solver with two random parameters: (i) market prices and (ii) wind generation. To analyze and forecasting electricity prices IOHMM approach was applied in order to generate electricity price scenarios in a day ahead market.

The main feature of this approach was that the switching nature of the electricity market can be represented by a set of dynamic models sequenced together by a Markov chain. The wind farm owner has been modeled as a risk-neutral agent. This method is useful for investment decision about new PSP while any risk aversion measures are not taken into consideration.

The Central Unit Commitment and Economic Dispatch (UC–ED) optimization model PowrSym3 was applied for the determination of the benefits of energy storage for the large-scale integration of wind power in the Netherland power system [125]. Multi Criteria Optimization Model based on heuristic algorithm and Monte Carlo Simulation was used to minimize the operating cost in wind and ESS (underground PSP, CAES, heat boiler). The integral approach in this research allowed a system-wide assessment of technical, economical and environmental aspects relevant for the exploration of possible synergies between wind power and energy storage integrated in the existing power supplies. Here, important conclusion has been drawn for the Dutch system that overall CO_2 emission will be more at low wind power penetration.

Jiang et al. [126] developed a robust optimization approach to accommodate wind output uncertainty with the objective of providing a robust unit commitment schedule for the thermal generators in the day-ahead market that minimized the total cost under the worst wind power output scenario. Robust optimization models had the randomness using an uncertainty set which included the worst-case scenario, and protected this scenario under the minimal increment of costs. The model incorporate a two stage min–max optimization problem based on Decomposition Algorithm and Monto Carlo Sampling approach in a day market for Wind–PSP system. The scheduling technique used by the author was probabilistic distribution. In the above problem, robust optimization tool was used incorporating to worst condition with high wind penetration and the solution obtained was highly sensitive to the transmission line capacity variation. Faias et al. [127], presented a dedicated methodology based on MILP using CPLEX solver to identify and quantify the occurrence of increasing integration of wind and its over-generation and to evaluate some of the solutions that can be adopted to mitigate this problem in Portuguese power system, where, the wind energy is expected to represent more than 25% of the installed capacity in near future. Historic Time Series extrapolation was used as forecasting technique. A technical and economical analysis was also carried out in order to design an additional energy storage system that totally offsets the wind energy curtailments but unable to achieve economic viability of solution due to high capital cost. The short-term optimal operation of an electric system comprising several thermal power plants and one PSP was studied in several scenarios of power demand and wind penetration in order to draw conclusions about the contribution of the PSP to system operation costs for an autonomous island [128]. MILP was used to obtain the optimal hourly thermal, hydro and pumping powers so that the generation cost of the entire system is minimized. The system operation has been studied under different demand and wind speed scenarios, the later being scaled to different wind penetration levels. Wind uncertainty was not considered to achieve the objective of minimization of greenhouse gasses effect. The basic objective (s), the merits as well as the demerits of these optimization techniques are presented in Table 4.

5.2. Artificial intelligent optimization techniques for Wind–PSP scheduling

Artificial intelligent (AI) is commonly defined as the science and engineering of making intelligent machines, especially intelligent computer programs [129,130]. Main AI techniques found in power systems applications are those, utilizing the logic and knowledge representations of expert systems, fuzzy systems, artificial neural networks (ANN) and, more recently, evolutionary computing. The applications and goals of these techniques and varieties of techniques owe to their great potentials to optimize technical and economical Wind–PSP challenges. In recent years, there have been numerous AI techniques implemented to solve the wind energy planning problems but specifically with Wind–PSP scheduling.

The AI based techniques reviewed in this study are PSO [131–134], Evolutionary algorithm (EA) [135], Genetic algorithm (GA) [136,137], Fuzzy logic [138,139], Mixed Integer Non-Linear programming (MINLP) using GAMS in single and Multi-objective problems. These techniques have been applied in most optimization problems as well as Wind–PSP scheduling.

A multi-pass iteration particle swarm optimization (MIPSO) to solve short term hydroelectric generation scheduling of a power system with wind turbine generators was addressed by Lee [131] to minimize the operating cost. MIPSO is a new algorithm for solving nonlinear optimal scheduling problems. A new index called iteration best (IB) is incorporated into PSO to improve solution quality. The concept of Multi-Pass Dynamic Programming is applied to modify PSO and improve computation efficiency. Weibull based probabilistic techniques using HOMER program was used for wind forecasting in an autonomous Wind–PSP system. Lee's method exhibited more accurate results as compared to other approach based on EP and PSO limited to large computational time. Pappala et al. [132] addressed a solution for a day-ahead operation of a system with thermal, nuclear, wind and pump storage units considering the demand and wind generation uncertainties. The author also reduced the stochastic error during wind forecasting. A new method for modeling the uncertainties in the cost model was successfully implemented using PSO. The nonlinear mixed integer multistage stochastic cost model was solved using the adaptive PSO. The robust solution provided by APSO will enable power system operator to plan the operation of the power system under the influence of demand and wind generation uncertainties. The proposed method gave high operating cost compared to the other methods. Siahkali [133] investigated an approach to solve the generation scheduling problem, considering reserve requirement, load generation balance and wind power generation constraints using PSO. This problem was applied to a test system which has pumped storage power plants to modify the uncertainties of wind power output and other parameters in power system. The approach was in the good agreement for optimal scheduling and provided best trade-off between the cost and constraints, however the wind uncertainties were ignored. Siahkali et al. [134] solved MINLP problem using PSO and the Global Variant-Based Passive Congregation (GPAC) to generate faster and near optimal schedule compared to the conventional PSO. The hybrid technique (GPAC–PSO) did not provide accurate results as PSO did.

Anagnostopoulos et al. [135] presented numerical methodology based on EA to solve single and Multiobjective Optimization problem for optimum sizing of the various components of a reversible hydraulic system i.e. PSP, designed to recover the electric energy, which was rejected from wind farms due to imposed grid limitations. The algorithm is applied to study a practical case using time variation data of rejected power from a number of wind farms installed in the island of Crete, Greece. The results showed that a well optimized design may be crucial for the technical and economic viability of the system. The free design parameters of the system and some critical financial parameters were also considered. In addition, the developed numerical tool was used to perform several parametric studies and sensitivity tests in order to analyze in depth the influence of the most important parameters on the plant operation and economic

Table 4
Comparison of various optimization techniques for wind–PSP scheduling.

S. N.	Problem type	Technique(s)/Approach (s)	Objective function (s)	Merit (s)	Demerit (s)	Market type	Forecasting technique	ESS type	Refs.
A	**Classical optimization techniques**								
1.	Linear programming optimization problem	– Interior point method	Maximization of profit	Provided best bidding strategy for Wind–PSP system	– Used energy equation for PSP – Required to implement this approach for large number of pumped storage plant	Autonomous island or power system	Monte Carlo	PSP	[110]
2.	Linear programming optimization problem	– Linear programming using CLP solver	Minimization of operating cost	Also considering the dynamic security criteria	– Not providing risk analysis	Autonomous Island or power system	Fuzzy clustering algorithm	PSP	[123]
3.	Two stage stochastic programming problem	– Mixed integer linear programming using – CPLEX solver	Maximization of profit	Useful for existing investment decision about new PSP	– Has not provided any risk aversion measurement	Spot or day ahead market	Input/Output Hidden Markov Model (IOHMM)	PSP	[124]
4.	Multi criteria optimization problem	– Heuristic algorithm – Monte Carlo Simulation	Minimization of operating cost	Provided maximum utilization of wind energy with the used of different energy storage devices	– Overall CO_2 emission will be more at low wind power penetration	Autonomous Island or power system	Wind speed interpolation	Underground PSP) UPSP-PSP-CAES-Heat Boiler	[125]
5.	Two stage min–max optimization problem	– Decomposition algorithm – Monte Carlo sampling approach	Minimization of operating cost	Provided robust optimization under worst condition with high wind uncertainty	– Optimal solution is highly sensitive to the transmission line capacity variation	Day ahead market	Probabilistic distribution	PSP	[126]
6.	Mixed integer linear programming problem	Mixed integer linear programming using CPLEX solver	Minimization of operating cost	Sensitive analysis has been performed to analyze the main factor that influence the wind curtailment	– Unable to achieve economic viability of solution due to high capital cost	Autonomous Island or power system	Historic time series extrapolation	PSP	[127]
7.	Mixed integer linear programming problem	Mixed integer linear programming using CPLEX solver	Minimization of Operating Cost	Minimizing the greenhouse gasses effect and avoiding wind curtailment	Not considering the wind uncertainty	Autonomous island or power system	None	PSP	[128]
B.	**Artificial intelligent optimization techniques**								
8.	Non-linear optimization problem	MIPSO	Minimization of operating cost	This approach provided the better result as compared to other approach based on EP and PSO	Take large time as compared to classical approach	Autonomous Island or power system	Weibull based Probabilistic techniques using HOMER program	PSP	[131]
9.	Single and multiobjective optimization problem	Evolutionary algorithm	Maximization of net present value or profit	This approached provided the good result for the high capacity wind farm	Recovered wind energy by this method only balances the system losses	Autonomous island or power system	Probabilistic distribution	PSP	[135]
10.	Multistage Stochastic Model	PSO	Minimizing the operating cost	Scenario reduction techniques reduced the stochastic error during wind forecasting	Solution provided the high operating cost	Day ahead market	Scenario reduction technique	PSP	[132]
11.	Mixed Integer Non- Linear Programming Problem	PSO	Maximization of profit	Provided the best trade-off between profit and constraints	Unable to considered the effect of wind uncertainty	Autonomous island or power system	None	PSP	[133]
12.	Mixed Integer Non- Linear Programming Problem	GPAC-PSO	Minimization of operating cost	GPAC-PSO provided the faster result as compared to conventional PSO	Conventional PSO provided the better results as compared to GPAC-PSO	Autonomous island or power system	None	PSP	[134]

13.	Multiobjective Optimization Problem	Genetic algorithm	Minimizing the operating cost	Used hybrid system of Wind–PSP–PV	Risk related to wind uncertainty is ignored	Autonomous island or power system	None	PSP	[136]
14.	Linear Programming optimization problem	Fuzzy clustering approach	Maximization of profit	Application of FCM for wind speed and acceptable power of grid clustering	Not considered the water storage equation for PSP	Autonomous island or power system	None	PSP	[138]
15.	Mixed integer linear programming problem	Fuzzy optimization based method Mixed integer non-linear programming (MINLP) using GAMS	Maximization of profit	Provided the best trade-off between profit and constraints	High startup and shut down cost	Autonomous Island or power system	None	PSP	[139]
16.	Mixed integer linear programming problem	Genetic Algorithm	Maximization of profit	The hybrid wind-solar-pumped-storage power system is used to maintain the advance stability of system.	No practical system was used	Autonomous Island or power system	None	PSP, battery	[137]
C	**Other promising techniques for future use**								
17.	Non-linear optimization based problem	Nash–Cournet model/non-linear optimization solver using PATH	Maximization of profit	Systematically extended to capture more uncertain effect across market	Practical system required to be considered for this approach	Unilateral market	None	None	[140]
18.	Simulation based problem	(Long run electric market simulator)LREMS Simulator based on game theory	Maximization of Profit	Game theory providing the natural modeling of the competition	Take very long time for simulation	Italian electricity market	None	None	[141]
19.	Non-Linear optimization based problem	Nash Equilibrium/Network optimization technique	Maximization of profit	Efficient bidding has been achieved equally for all generators	Assumed the bidders cost that effect the actual system result	Bilateral electricity market	None	None	[142]
20.	Mixed integer linear programming problem	Greedy algorithm/Nash equilibrium/Evolutionary game theory tool/MILP Solver	Minimize of the operational cost	Provided multi agent based simulation		Wholesale electricity market	None	None	[143]
21.	Decision based problem	Risk analysis/Nash equilibrium	Maximization of profit	Effectively control the risk and attain greatest overall benefit.	Required to considered any practical system	Offshore wind farm	None	None	[144]
22.	Linear complementarity problem	Nash–Cournot model/Chance constrained programming	Maximization of profit	Analyze the effect of wind location on the overall profit		Autonomous island or power system	None	None	[145]
23.	Decision based problem	Cooperative game theory/ Sharply value	Minimization of imbalance cost	Represent the cost allocation technique	Required to implement this approach for the large number of wind power producer	Autonomous island or power system	None	None	[146]
24.	Multi criteria optimization problem	Game theory/Genetic algorithm based approach	Maximization of profit	Select the effective bidding strategy so that every power producer maximize their own profit simultaneously	Required to implement this approach for large number of PSP and wind units	Day ahead market	None	PSP	[147]
25.	Mixed integer non-linear programming	MINLP with AMPL, KNITRO solver	Maximization of profit	Simple approach, fast approach, optimal result.	Not considered the uncertainty effect of wind	Autonomous system	None	PSP	[148]

behaviour. Xiaoyu et al. [136] described a hybrid wind/PV system using pumped-storage station to offset the effects of the inclusion of wind or wind power and to transfer energy form low-use periods to peak-use periods instead of battery. The multiobjective optimization problem was optimized by using GA, under the economic and security criteria condition. Results showed that the optimal system has the characteristics that the LPSP (loss of power supply probability) is merely zero and the CUE (cost of unit energy) is lowest. This technique is good for hybrid system like Wind–PSP-PV in absence of risk related to wind uncertainty. Yan et al. [137] used an improved GA to solve the MILP problem i.e. hybrid wind-solar-pumped -storage power system in autonomous island. In this system, model is brought forward, and the optimization method is applied, which effectively uses wind and solar resource, advancing stability of system, and reducing investment and run/management of the system. The hybrid wind-solar-pumped-storage power system was used to maintain the advance stability of the system. Li-jie et al. [138] modeled the wind farm and pumped storage power plant operation, targeting the economic benefit of hybrid wind power and pumped hydro storage systems. The stochastic nature of load and wind energy was addressed using scenarios developed through fuzzy clustering technique. The application of Fuzzy C-means (FCM) was used for wind speed and acceptable power of grid clustering. It has been found that the combined revenue of wind farm can be improved by the proper capacity allocation of pumped storage power station. The authors have not considered the effect of wind uncertainty and for PSP; energy equation has been used in place of water equation. Meanwhile, a fuzzy optimization-based method was developed to solve power system generating scheduling problem using fuzzy membership functions (MFs) for objective and some constraints [139]. This fuzzy generating scheduling problem was firstly converted to a crisp formulation and then solved using GAMS software based on MINLP. This problem was applied to a test system which has pumped storage power plants to modify the uncertainties of wind power output and other parameters in the power system. The results of this problem were compared with the results of crisp solution results and values of the total profit. This technique provided the best trade-off between profit and constraints but failed to minimize high start-up and shut-down cost.

The basic objective(s), the merits as well as the demerits of these optimization techniques are presented in Table 4.

5.3. Other promising techniques for future use in Wind–PSP scheduling

Apart from the optimization techniques discussed in the previous sub sections, other promising techniques which can be used in finding the optimal scheduling and operation of Wind–PSP are Nash–Cournot Model/Non-linear Optimization Solver using PATH [140], Long Run Electric Market Simulator (LREMS) based on Game Theory [141], Nash Equilibrium/Network Optimization Technique [142], Greedy Algorithm/Nash Equilibrium/Evolutionary Game Theory Tool/MILP Solver [143], Risk Analysis/Nash Equilibrium [144], Nash-Cournot Model/Chance Constrained Programming [145], Cooperative Game Theory/Sharply Value [146], Game Theory/GA [147], and MINLP with AMPL, KNITRO Solver [148]. All these techniques can be used to solve the Wind–PSP problem as decision making and linear/non-linear problem considering the risk assessment. As per recent research studies, Game theory based models seem to be very helpful to analyze the natural behavior of the market under uncertain condition in deregulated market. These approaches are continuously drawing the attention of researchers in solving such decision making problems to find fast and the optimal solution in cost effective manner as described below.

In the deregulated market, game theoretical based model seem to be very helpful to analyze the natural behavior of market under uncertainties. In this market, every entity choose the various operation like trading, buying or auctioning in order to increase the revenue across them [149]. Due to this type of behavior, deregulated market also referred as competitive market, where every player tries best to be in competition by optimizing their operation in efficient way. Kannan et al. [140] used this model to analyze the various dynamic and static impact of system on the market under uncertain condition. Migliavacca et al. [141] used game theoretical model to analyze the effect of market competition in the simulator used for providing the long term simulation. Different game theory based models have been used for designing the optimal bidding strategy under the electricity market [141–146].

Due to wind variability, and to maintain the security and safety to the market operation, it is required to perform the risk analysis. Ming et al. [144], provided the risk analysis on the offshore wind farm consisting of various steps like risk identification, risk measurement and the risk allocation. For this analysis, Game theory based Nash equilibrium technique has been used, which effectively controlled the risk and attained greatest overall benefit. Game theory based model has been used to analyze the effect of uncertainty on the wind integrated electricity market, but avoided to perform any risk analysis [145,146]. In future work, it is required to perform the risk analysis across the wind uncertainty to maintain the market security and safety. It is also required to further reduce the effect of uncertainty risk by operating the wind system with PSP. A game-theoretical model has been used for bidding strategy of a generation company considering wind unit as a price-maker, in a day-ahead electricity market [147]. Optimization of the proposed model has been carried out by using GA. Similar kind of decision making approach was adopted by Dhillon et al. [148] for profit maximization. The MINLP type problem was formulated in AMPL using KNITRO as main solver. This approach was simple and fast in evaluation of autonomous Wind–PSP system and provided the efficient and robust solution of small and large problems. The authors did not consider the wind uncertainties.

To manage the risk across the Wind–PSP system, it is required to find the level of risk across each varying levels of scenarios. One of major advantage of using risk management strategies across the Wind–PSP system is to build the system to bear the risk during day ahead scheduling. To apply the risk management strategies on the Wind–PSP system, Taguchi technique can be a promising technique for future use. According to Taguchi's principle, the selection of a “top-down” or a “bottom-up” approach depends on whether the product in question is in the design phase or in the production phase. Taguchi suggested the experimental design technique to reduce variation in design variables. Taguchi's robust design approach improves quality in order to achieve consistency of performance. This method may be a systematic and efficient approach for experimentation using Orthogonal Arrays (OA) to determine the near-optimum settings of design parameters for performance and cost. [150–152].

The basic objective (s), the merits as well as the demerits of these optimization techniques are presented in Table 4.

6. Conclusions

In the present study an attempt has been made to review the basics of wind power, ESSs, PSPs, Wind–PSP system including basic concept, benefits, growth and current status, operational formulation, challenges and opportunities for Wind–PSP development under deregulated market, deregulated market types, scheduling of Wind–PSP, optimizations techniques and methodologies used in optimal operation and scheduling of Wind–PSP under

deregulated market. An overview of the relevant aspects related to Wind–PSP system and impact of Wind–PSP on the operation of supply system in present deregulated market has been presented. Challenges and opportunities for Wind–PSP development under deregulated market have also been discussed along with measures to overcome their limitations.

Several studies have already addressed the higher penetration of wind power globally in deregulated market. The growth rate of wind generation increased rapidly since last few decades. The growth rate of cumulative installed wind capacity in Europe, North America, Asia, Latin America, Pacific and Middle East and Africa regions remarkably hit at 18.70% till the end of 2012. Among them Asia, North America and Europe are the major key players in installation of highest wind capacity, though, these regions generally followed the pool based and open access type of deregulated market structure. In the same sequence, various electrical utilities shifted towards the deregulated market structure to provide efficient power system with better quality of service. Countries like USA, UK, Spain and Norway started deregulating and privatizing their power market structures, which are characterized by open competitive energy markets, unbundling electricity services and open access to the network after 19th century.

The various optimization techniques used for Wind–PSP operation by different researchers revealed that one is generally faced with fundamental conflict between accuracy, reliability and computational time while finding a global optimal solution of complex multi-objective and decision making optimization problems with risk assessment, particularly those with many local optima. It is often impossible to arrive at solution that optimizes all objectives without a trade-off. Consequent upon that fact, it can be concluded that hybrid of two or more or new multi-objective optimization decision making techniques with risk assessment are promising research areas in the field of Wind–PSP operation. By doing so, the techniques would have combined their strength and mitigate each other's limitations in arriving at the best possible solution. The uncertainties involved in system planning and operation become larger and certainly new methods need to be developed to analyze and foresee the behavior of the systems. Earlier researchers have used many optimization techniques to solve wind PSP scheduling problem. EA based, GA with LVQ, HIDSS for credit risk evaluation based on neural networks and GAs, NSGA-II may be others techniques in solving these kind of problems in future.

7. Recommendations

It is seen that, Wind–PSP has gained lot of attractions in the power sector due to its flexibility to change the output power quickly and to follow the short term variations on wind power, and most significantly, to support the exploitation of RESs like wind and photo-voltaic. Based on the published research review presented in this study, following recommendations and suggestions have been made for the development of Wind–PSP systems:

i. Research work is required in network integration of medium/high penetration of wind energy.
ii. New options of utilizing underground caverns or subsurface or offshore reservoirs for pumped hydro application in the areas without mountains need to be explored.
iii. Wind–PSP technology can use modern efficient reversible pump-turbines, variable speed pumped turbines, new controls such as variable frequency converters and advanced generator insulation systems, as well as improved underground tunneling construction methods and design capabilities.
iv. Due to complexity of the system, many constraints need to be considered simultaneously such as, frequency variations, voltage stability, power imbalance, related capacity, system efficiency, operational cost, and reliability in the operation of Wind–PSP.
v. International market drivers may develop a new energy market structure, where transmission providers also set benefits from long-term agreements with energy storage facility developers.
vi. Optimization techniques such as: EA based, GA with LVQ, HIDSS, NSGA-II can be used to find global optimal solution of complex computational problems with uncertainties for Wind–PSP operation.

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